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I am submitting herewith a thesis written by Edward L. Hamlett entitled "Sampling at the Magnetohydrodynamic Generator Cyclone for Seed Recovery." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

Lloyd W. Crawford
Lloyd W. Crawford, Major Professor

We have read this thesis
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Accepted for the Council:

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Graduate Studies and Research

X

SAMPLING AT THE MAGNETOHYDRODYNAMIC

GENERATOR CYCLONE FOR

SEED RECOVERY

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Edward L. Hamlett

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The author expresses manifest appreciation to the many people who have assisted in the consummation of this thesis. Sincere appreciation is given to Dr. Joel Muehlhauser and his technical crews for their collaboration during cyclone sampling and sample preparation. In particular, the author wishes to acknowledge the assistance of Dr. Kenneth Tempelmeyer during the cyclone test stage and Dr. Lloyd Crawford, the author's major professor, during refinement of this report. The excellent typing and administrative work of Mrs. June Jarrell is acknowledged and appreciated.

The author is indebted to his wife, Janet, and his grandparents, James and Roxie Hamlett, for their constant encouragement.

ABSTRACT

This study is devoted to a quantitative analysis of seed recovery data obtained from collection and processing of the by-products from the UTSI Magnetohydrodynamic (MHD) generator test facility. In particular, the cyclone collectors are studied to determine what portion of all exhausting material they collected. The cyclone design considerations are covered and total collection per run given.

The efficiency of efforts at removal of the K_2SO_4 or K_2CO_3 seed from flyash collected in the cyclone hoppers and particulate collected from the cyclone stack is presented. The percentage of seed material at various key locations is also given.

The significance given to seed recovery/makeup costs compared to capital costs and fuel costs is presented.

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NOMENCLATURE

C_o	Cyclone shape related constant
d_o	Outlet diameter
d_p	Particle diameter
D_c	Cyclone barrel diameter
D_{theor}	Theoretical cyclone collection cut size, diameter
f[ ]	Function of [ ]
F_s	Separating force
F_R	Resisting force
g	Gravitational constant
G_L	Grain loading
h	Overall pressure drop
I_C	Insoluble portion from chunks
I_E	Insoluble portion from exhaust
I_D	Insoluble portion from dust
I_T	Total insoluble seed
K	Constant
M_P	Mass of particle
N	Number of revolutions of gas stream in cyclone
Q_s	Specific gas flow rate through cyclone barrel cross section
r	Radius
R	Gas constant
R_L	Rate of seed loss

R_R	Rate of seed recovery
R_u	Rate of seed unaccounted for
S_{C1}	Seed recovered from washing chunk
S_{C2}	Seed recovered from crushing washed chunks and rewashing
S_D	Seed recovered from washing dust
S_E	Seed recovered from washing exhaust
S_I	Seed input
S_{IM}	Seed recovered from impingers
S_O	Total seed collected from cyclone outputs
T_N	Location of thermocouple "N"
v_t	Tangential velocity
V_p	Particle velocity
W_C	Weight of collected chunks
W_D	Weight of collected dust
ε	Cyclone efficiency
γ_d	Density of dust
ρ	Density
μ	Viscosity

CHAPTER I

INTRODUCTION AND HISTORY OF CYCLONES

It is necessary to collect the by-products of combustion in the open cycle magnetohydrodynamic (MHD) energy generation process due to economic concerns with seed material costs. This economic factor was recognized and allowed for in the preliminary design plans for The University of Tennessee Space Institute (UTSI) generator test facility (1:45)[1]. Seed collection efficiencies of 98 percent or greater were once considered a requirement to keep seed makeup costs between 3 and 10 percent of fuel costs (2:8). Cost of electricity (COE) calculations now show that capital and fuel cost, particularly the former, dwarf the seed cost (3:73). Nevertheless, without government regulations and restrictions on exhaust emissions from energy generating plants, some method of generator flyash collection for seed recovery is required.

The temperature at the inlet of the primary collector is in the neighborhood of 3,000°F (4:6). The material to be collected ranges in diameter from micron size dust to hard ball-size clinkers. Due to the aforementioned service

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[1]Numbers in parentheses refer to similarly numbered reference in the List of References and the page number of the referenced text.

conditions, the simplest form of flyash collection device was needed: a device that could be sufficiently cooled to withstand temperatures at which steel has normally lost its mechanical strength; a device devoid of parts that would quickly erode or become inoperative; a device capable of handling the variance in input size. The simple cyclone was chosen because it met all necessary qualifications.

As used in industry the term "cyclone" includes mechanical collectors, without moving parts, that use centrifugal force to separate particles from a gas stream. The dust laden gas stream channels tangentially into the cyclone barrel, which imparts a spinning, vortexed flow pattern to the gas-dust mixture. Centrifugal force separates the dust from the gas stream. The dust travels first to the walls of the barrel, then down along the conical section to the dust outlet hopper. The spinning gas also travels down along the wall toward the apex of the cone, but reverses direction in the center of the cone, and leaves the cyclone through the gas outlet tube at the top (5:64).

The constantly rising cost of power generated from domestic and nondomestic fuels coupled with the uncertain foreign fuel market are making MHD an economically viable alternative. The increased costs of the MHD topping plant are also defrayed by the near 50 percent increase in efficiency realized over today's best generating plants (6:88).

This thesis shall seek to explain the considerations involved in cyclone design and results of flyash collection in the UTSI-MHD cyclone. The literature available on the cyclone is fairly sparse. Therefore, the rest of the first chapter has been devoted to the history of cyclones. The results of early studies and design concerns addressed by the founding fathers of cyclonic separation are presented. The state-of-the-art design considerations in efficient cyclone fabrication are discussed in Chapter II. The size relationships between the various cyclone components and the profound effect varying one component has upon collection efficiency are considered. Test data from the water cooled UTSI cyclone are presented in Chapter III. The final chapter, Chapter IV, is devoted to an evaluation of those results and conclusions.

History of Cyclones

Cyclones were the first and are still the most common of the various dust collection devices (7:41). The first cyclone was probably that of the Knickerbocker Company, in this country. The Knickerbocker cyclone had its design completed in 1885. Figure 1 and Figure 2 show reproductions of the German patent 39,219 (1885) granted the Knickerbocker Company (8:97). Several United States patents were also awarded for cyclones in the same time period; they were 325,521 (1885), 370,020 (1887), and 389,786 (1889).

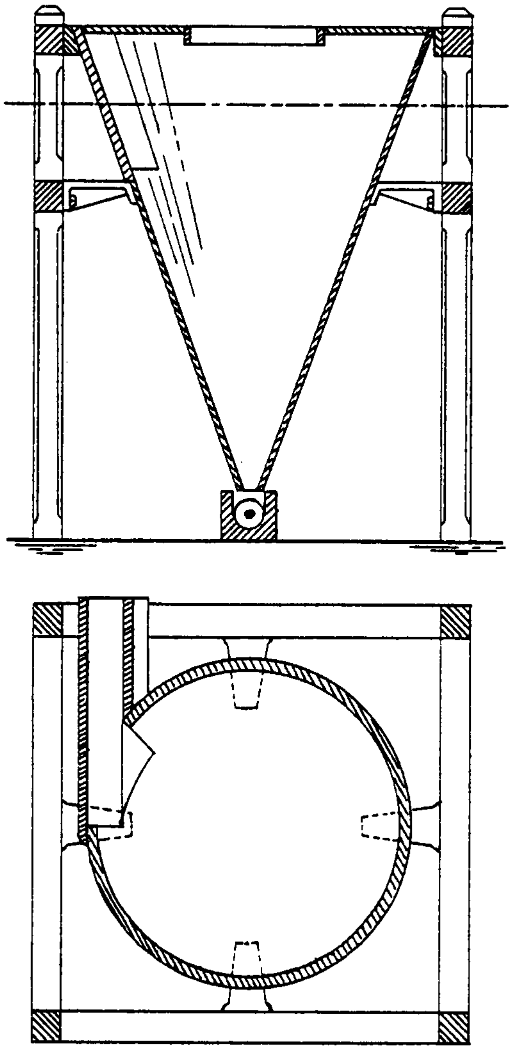

Figure 1. Figures 1 and 2 of German Patent 39,219.

Reference: <u>Cyclones in Industry</u>, Ed. K. Rieterna and C. G. Vernier, <u>Elsvier Publishing Co.</u>, Amsterdam, 1961, p. 97.

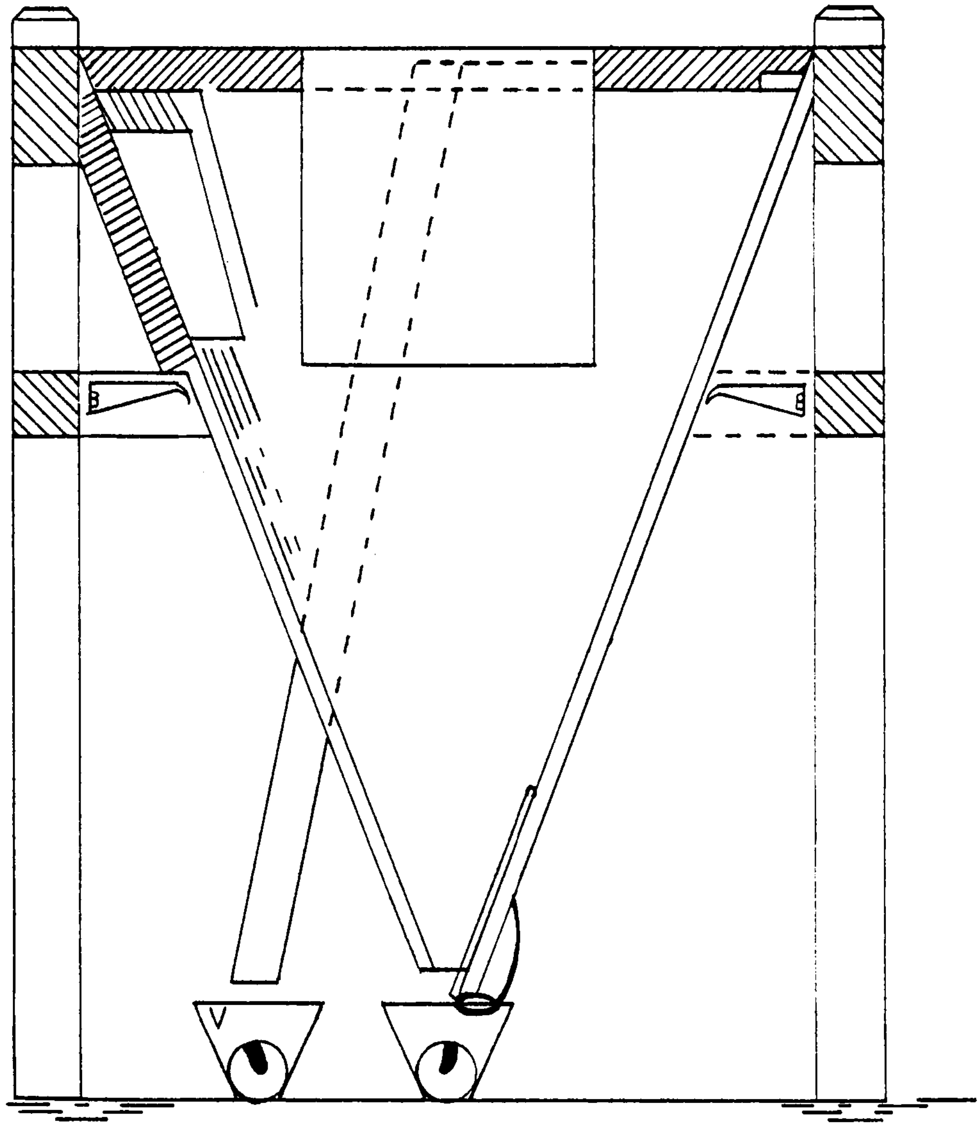

Figure 2. Figure 5 of German Patent 39,219.

Reference: Cyclones in Industry, Ed. K. Rieterna and C. G. Vernier, Elsvier Publishing Co., Amsterdam, 1961, p. 98.

Hydraulic cyclones were designed at the same time, as exemplified by United States Patent 453,106 (1891) (9:869).

There are many reasons why cyclones are the most common dust collection device. Cyclones have acquired their unique position due to their lack of moving parts, their large capacity, and their varied applications. Table 1 shows a cost comparison of many common collection devices. The early work that was performed to determine the parameters which control a cyclone's operational efficiency is in part responsible for the cyclone's varied applications.

The Work of Van Tongeren

Van Tongeren performed what is considered to be the first extensive investigation into the flow pattern of cyclones. He performed the major portion of his work in the 10 year period before 1939. Figure 3 shows a rough sketch of the Van Tongeren cyclone. The sketch shows a double eddy form of flow produced by a gas that is nominally moving in the direction shown by Figure 4.

In the works of Van Tongeren we find no mention of how he measured gas flow. He also makes no mention of whether the flow lines in Figure 4 are the result of an artist's impression of the results he obtained or the result of measurement (10:753).

Since Van Tongeren's early studies there have been three other major investigations into flow patterns in gas cyclones. These investigations were performed by Shepherd

TABLE 1

APPROXIMATE CHARACTERISTICS OF DUST AND MIST COLLECTION EQUIPMENT

Equipment Type	Purchase Cost[a] ($/cfm)	Smallest Particle Collected (microns)[b]	Pressure Drop (in H_2O)	Power Used[c] $\frac{kw}{1000\ cfm}$	Remarks
A. Settling Chambers 1. Simple	0.1	40	0.1-0.5	0.1	Large, low pressure drop, pre-cleaner
2. Multiple tray	0.2-0.7	10	0.1-0.5	0.1	Difficult to clean, warpage problem
B. Inertial Separators					
1. Baffle chamber	0.1	20	0.5-1.5	0.1-0.5	Power plants, rotary kilns, acid mist
2. Orifice impaction	0.1-0.4	2	1-3	0.2-0.6	Acid mists
3. Louvre type	0.1-0.4	10	0.3-1	0.1-0.2	Flyash, abrasion problem
4. Gas reversal	0.1	40	0.1-0.4	0.1	Precleaner
C. Cyclones					
1. Single	0.1-0.2	15	0.5-3	0.1-0.6	Simple, inexpensive, most widely used
2. Multiple	0.3-0.7	5	2-10	0.5-2	Abrasion and plugging problems
3. Mechanical	0.2-0.7	5	-	0.5-2	Compact

TABLE 1 (Continued)

Equipment Type	Purchase Cost[a] ($/cfm)	Smallest Particle Collected (microns)[b]	Pressure Drop (in H_2O)	Power Used[c] kw/1000 cfm	Remarks
D. Scrubbers					
1. Cyclonic	0.3-1.2	5	2-8	0.6-2	Modified dry collector
2. Inertial	0.5-1.2	2	2-15	0.8-8	Abrasion problem
3. Packed	0.3-0.7	5	0.5-10	0.6-2	Channeling problem
4. Mechanical	0.5-1.4	2	-	2-10	Abrasion problem

[a]Steel construction, not installed, includes necessary auxiliaries, 1969 prices.

[b]With ~90-95% efficiency by weight.

[c]Includes pressure loss, water pumping, electrical energy.

Source: Sax, N. Irving. Industrial Pollution, Reinhold Publishing Company, New York, 1974, p. 398.

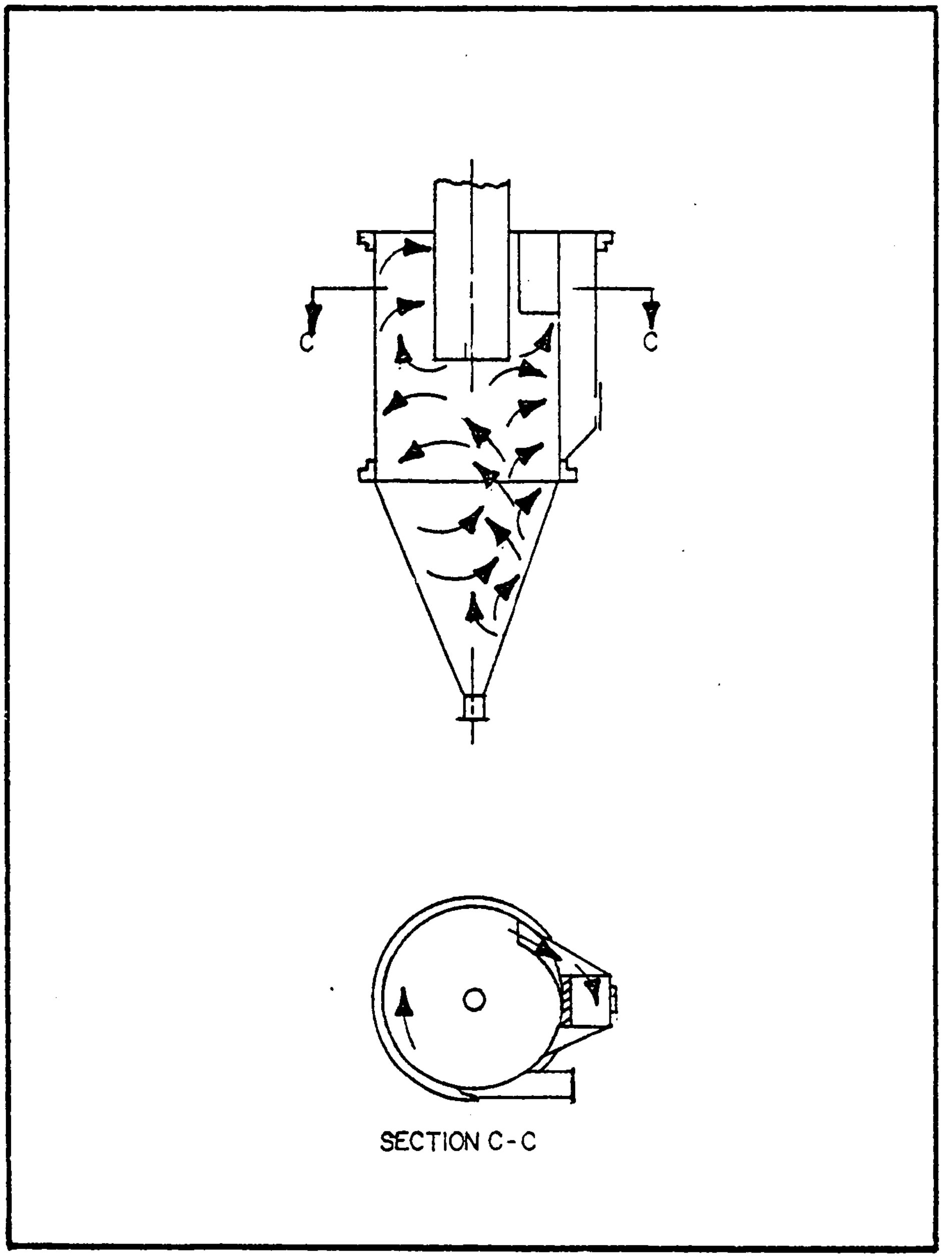

Figure 3. Van Tongeren Cyclone.

Reference: Jackson, R. Mechanical Equipment for Removing Grit and Dust from Gases, The British Coal Utilization Research Association, Chevey & Sons Ltd., Barnbury, England, 1963, p. 77.

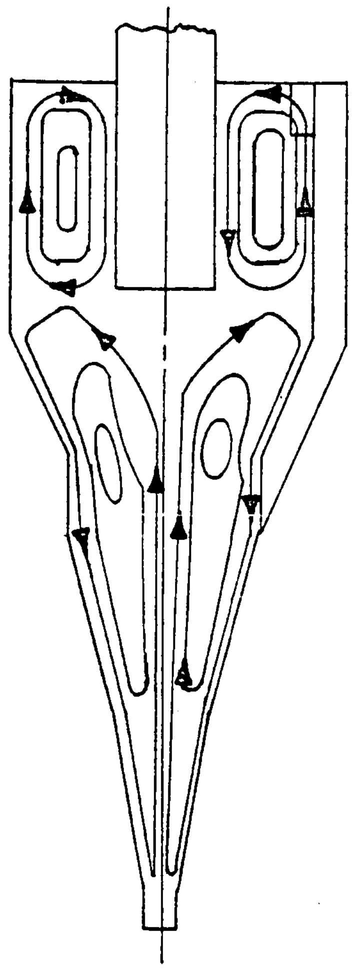

Figure 4. Double Vortex Flow in Cyclone.

Reference: Jackson, R. Mechanical Equipment for Removing Grit and Dust from Gases, The British Coal Utilization Research Association, Chevey & Sons Ltd., Barnbury, England, 1963, p. 78.

and Lapple (10) in 1939, by Ter Linden (11) in 1949, and by First (12) in 1949.

The Work of Shepherd and Lapple

In 1939 Shepherd and Lapple used a transparent model to determine the flow pattern within cyclones (13:973). They placed a number of short rayon streamers at various points along the inner glass wall to determine the direction of gas flow. The Shepherd-Lapple cyclone is shown in Figure 5. Table 2 shows the conditions of the test carried out by Shepherd and Lapple. Some of the results obtained by Shepherd and Lapple were confirmed in 1951 by the work of Stairmand (14:215). Some of Stairmand's results are at variance with Shepherd and Lapple for positions near the walls and near the axis. Shepherd and Lapple's results are probably unreliable due to the comparatively large width of the pitot static tube they used. Shepherd and Lapple commented that:

> No definite radius, marking the outer limit of the outer spiral could be observed; a reasonable interpretation of streamer and pitot tube determinations indicated that this radius varied approximately with the size of the exit pipe and was roughly equal to the exit pipe radius.

It is now known that in vortex flow streamers are not a reliable guide to flow direction. Stairmand obtained an inner vortex of uniform radius equal to half the radius of the exit pipe by calculation and observation of the inner core of a modern hydraulic cyclone (13:972).

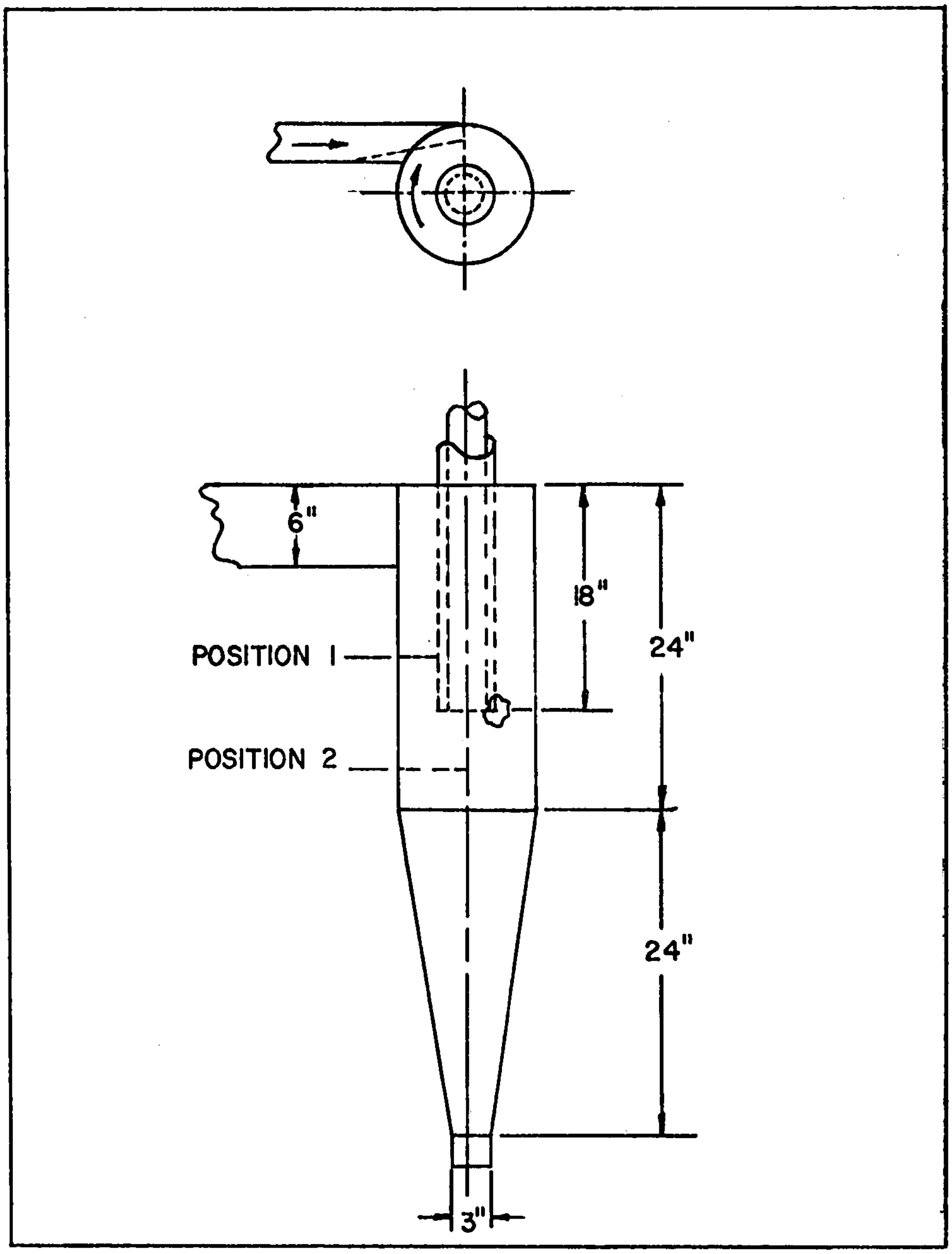

Figure 5. Experimental Cyclone Used by Shepherd and Lapple.

Reference: Jackson, R. Mechanical Equipment for Removing Grit and Dust from Gases, The British Coal Utilization Research Association, Chevey & Sons Ltd., Barnbury, England, 1963, p. 78.

TABLE 2

CONDITIONS OF TEST

Exit Duct Diameter, Inches	Inlet Width, Inches	Traverse Position	Inlet Velocity, Ft/Sec
5.6	2-5/8	1	69
5.6	2-5/8	2	69
5.6	1-5/16	1	127
5.6	1-5/16	2	127
2.75	3.0	1	37
2.75	3.0	2	37

Reference: Jackson, R. Mechanical Equipment for Removing Grit and Dust from Gases, The British Coal Utilization Research Association, Chevey & Sons Ltd., Barnbury, England, 1963, p. 79.

The Work of Ter Linden

The work of Shepherd and Lapple did not show radial or vertical velocities. Shepherd and Lapple's total velocities are inconsistent with their horizontal velocities and their angles of flow. It is therefore impossible to construct a three-dimensional model of what is going on within their cyclone.

The work of Ter Linden (11) does not contain this shortcoming but his work has been performed for only one shape cyclone. Therefore, Ter Linden's work does not have generality. However, it is very valuable because it is a detailed study of a particular type cyclone (14:83).

The tangential, radial, and vertical velocities together with the total and static pressures arrived at by Ter Linden are shown in Figures 6, 7 and 8. Figure 6 is not dissimilar to the figures produced by Shepherd and Lapple, but it takes the information much further.

The tangential velocity shown in Figure 6 is dominant, except in the region near the axis. The tangential velocity clearly controls the stability of the system. The radial flows fall into two regimes corresponding to, but not exactly like those of the tangential flows. In the outer region the flow is shown to be at a low rate toward the axis, while the flow in the inner region is at a high rate away from the axis. These velocity values were used by Ter Linden to give an average

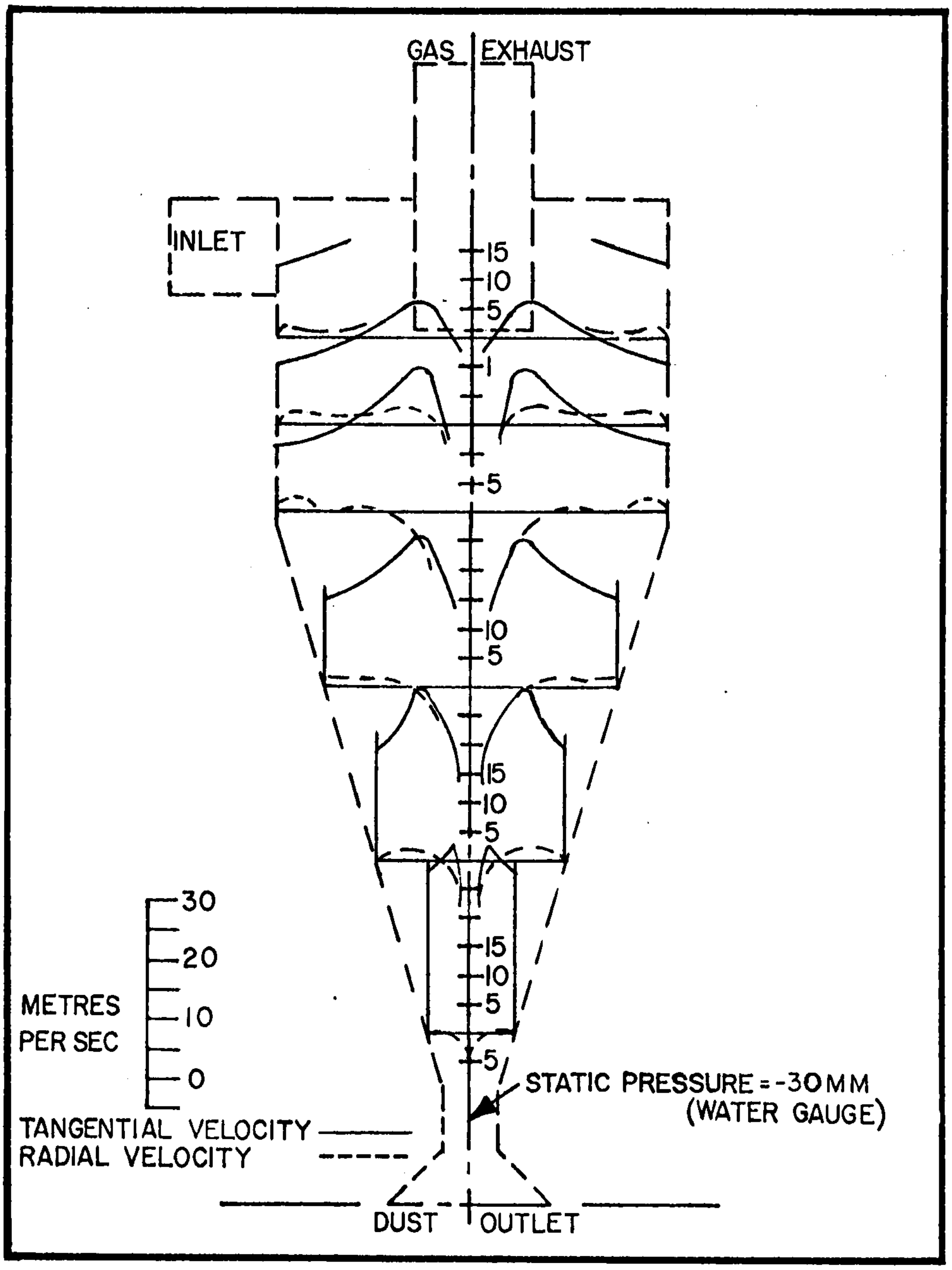

Figure 6. Tangential and Radial Velocities in a Cyclone.

Reference: Ter Linden, A. "Investigation into Cyclone Dust Collectors," Proceedings of the Institution of Mechanical Engineers, London, England, Vol. 160, January 1949, p. 236.

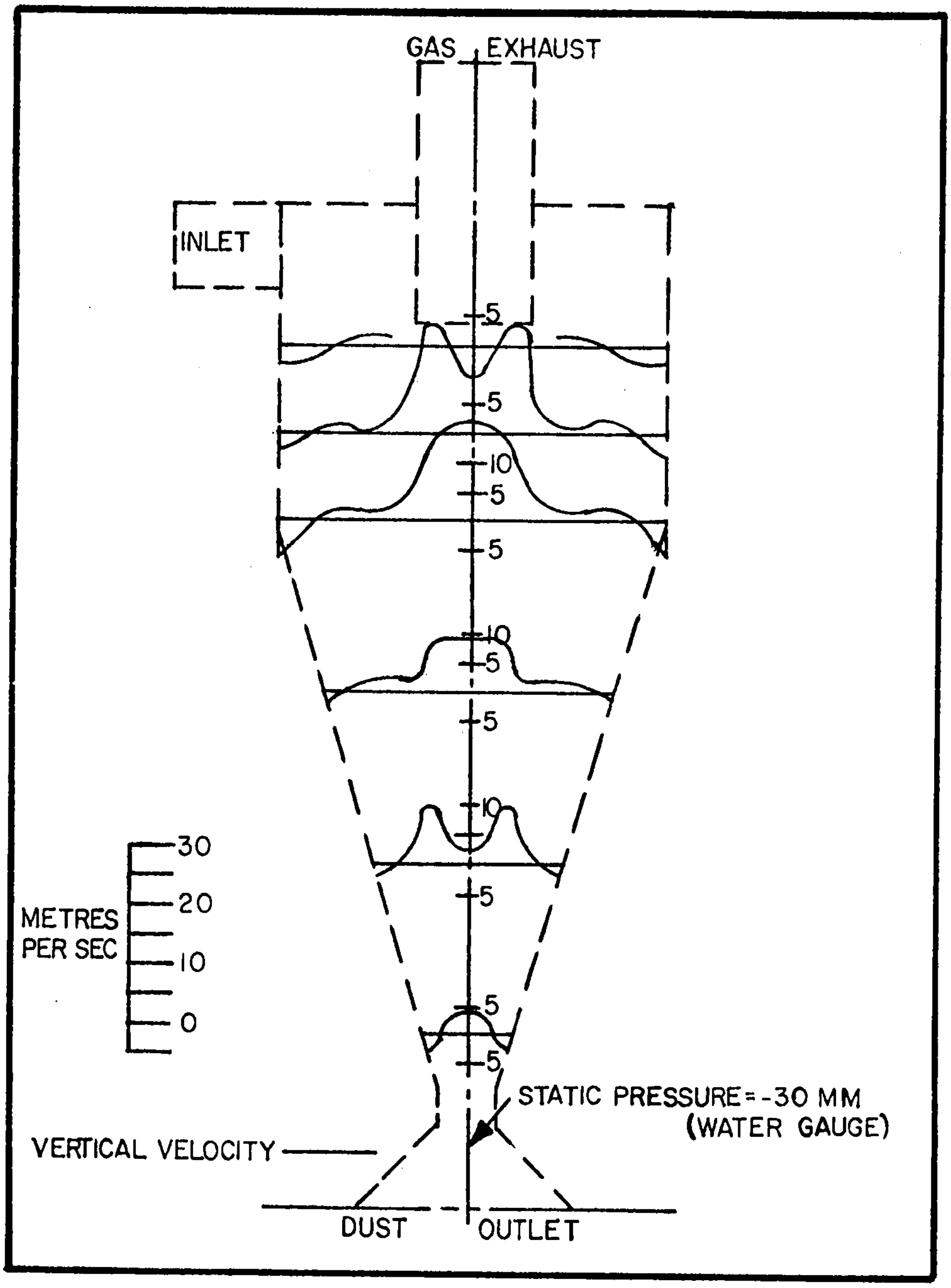

Figure 7. Vertical Velocities in a Cyclone.

Reference: Ter Linden, A. "Investigation into Cyclone Dust Collectors," Proceedings of the Institution of Mechanical Engineers, London, England, Vol. 160, January 1949, p. 237.

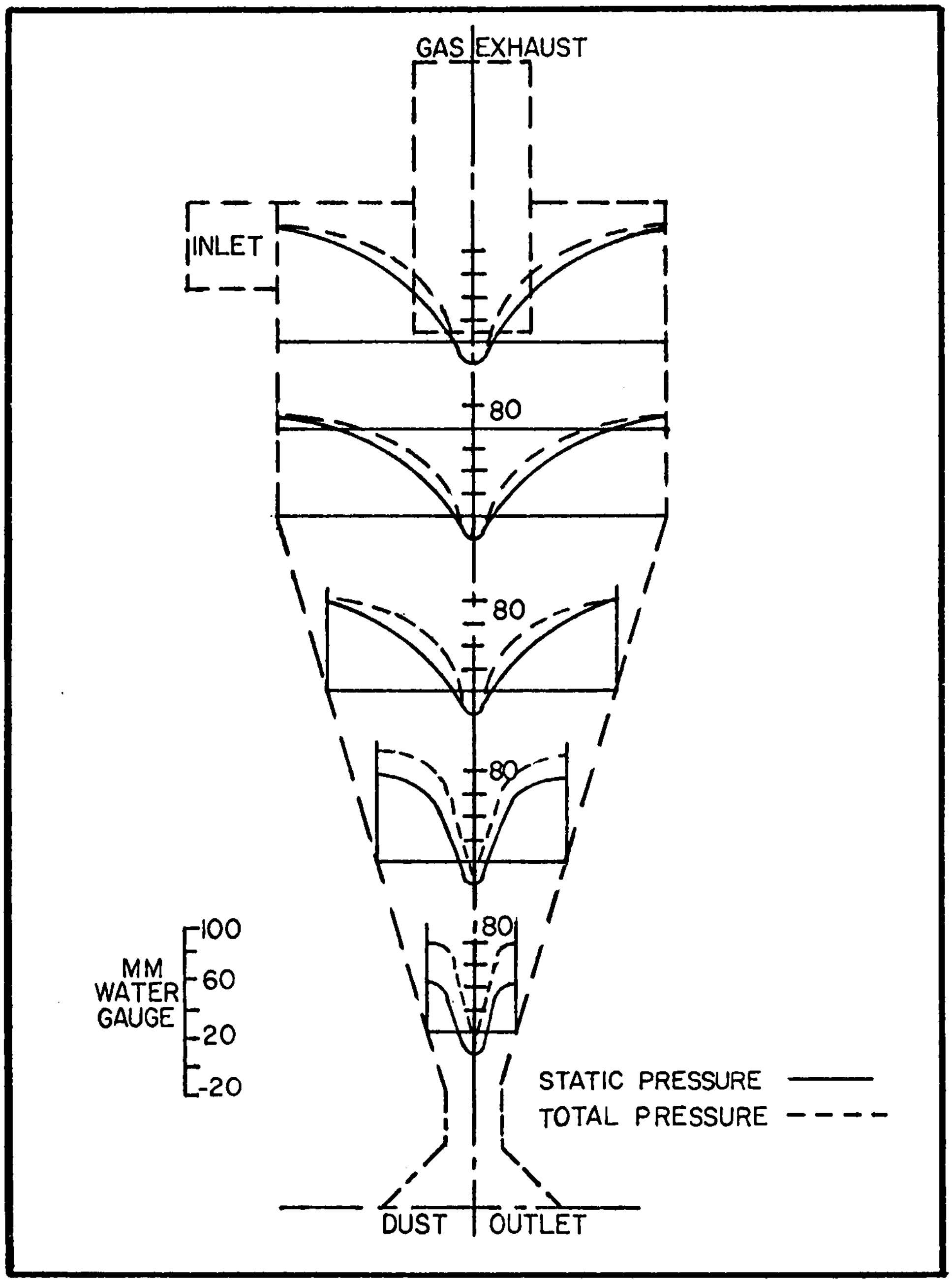

Figure 8. Total and Static Pressures in a Cyclone.

Reference: Ter Linden, A. "Investigation into Cyclone Dust Collectors," Proceedings of the Institution of Mechanical Engineers, London, England, Vol. 160, January 1949, p. 236.

value of the core radius as 65 percent of that of the exit pipe (11:235).

The vertical velocities arrived at by Ter Linden in Figure 7 show a condition in which the central flow could become negative. It has since been shown that this condition takes place whenever the gas exhaust diameter is over one-half the cyclone diameter (13:84).

Figure 8 shows no rapid changes in static or total pressures, but emphasizes the great differences in pressure across any horizontal plane in the Ter Linden cyclone. The static pressure at the walls is approximately equal to the inlet static pressure. There is considerable negative pressure at the axis of this figure. It is known that the negative pressure may extend into the dust hopper. Small holes in the dust hopper or near the cyclone axis give rise to considerable inflow of air and profoundly affect the flow pattern (11:235).

The Work of First

First made a detailed exploration into the flow patterns in 4, 8, and 12-inch diameter cyclones (12). First varied many of the shape dimensions so he might get complete information on cyclone dimensional performance interrelationships. First covered the effect of cone length, exit pipe insertion, outlet diameter, relationships between the tangential velocity (v_t) and radius (r), effect of inlet height, inlet width, etc. First's results shall be included in the next chapter, which includes a section on how to predict a cyclone's efficiency by its design.

CHAPTER II

DESIGNING FOR CYCLONE EFFICIENCY

Before considering the effect of various factors on efficiency, it is necessary to differentiate between the two forms in which cyclone efficiency is expressed--grade efficiency and mass efficiency. The grade efficiency is usually given in the form of a curve which expresses the weight percentage caught of each size of particle. Figure 9 shows the grade efficiency curve. If the size grading of the particles in the inlet gas is known, then from the grade efficiency curve the weight of particles in each size grade that are caught can be calculated, and hence the total weight percentage of all particles that are collected can be determined. This is the mass efficiency. Obviously, with a different initial size grading a different mass efficiency is obtained. For this reason, a statement of the mass efficiency of a collector is meaningless unless the size distribution of the input solids is known. Nevertheless, since the mass efficiency is a single figure, say 95 percent, it is easier to express and measure than is the grade efficiency. In addition to weight of input and collected solids, it requires the determination of size analysis of the solids present in at least 2 of 3 positions: inlet, and gas or dust exits.

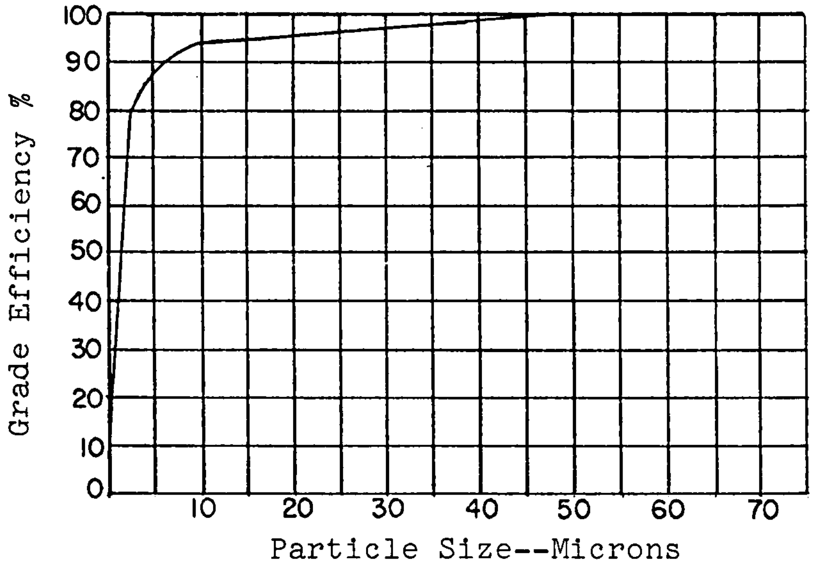

Figure 9. Fractional Efficiency Curves for 200 mm Diameter Cyclones, Inlet Velocity 15·2 m s^{-1}, Solid Density 2000 kgm^{-3} in Air at 20°C., High Efficiency Cyclone.

Reference: Strauss, W. Industrial Gas Cleaning, Pergamon Press, New York, 1975, p. 248.

For these reasons it is often used in discussions of the relative merits of different collectors. It cannot be too strongly emphasized that unless the dusts, entering each of the collectors under comparison, can be regarded as identical, the mass efficiencies cannot be used as reliable criteria in the comparison.

Since cyclones differ in size and shape, and may be operated under different conditions and with different types of dust, it is helpful in any comparison of a number of cyclones to reduce the performance figures to a standard form, though this is not always possible because of lack of data. The more basic method of expressing efficiency is the grade efficiency curve.

Calculation of Grade Efficiency

Many attempts have been made to calculate the effect upon cyclone efficiency of changes in cyclone diameter, gas outlet diameter, inlet width or area, cone length, particle size, and pressure drop. Since the behavior of a particle in a cyclone depends upon parameters characteristic respectively of the particle, the suspending gas and the cyclone, the efficiency of collection of a particle is as follows:

$$\varepsilon = \frac{\text{weight of collected particles}}{\text{weight of input particles}} \qquad (2.01)$$

A cyclone collector is a structure without moving parts in which the velocity of an inlet gas stream is transformed into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body. Cyclones are the simplest and cheapest of the standard collection devices (15:359).

Structurally, a cyclone must have an axial gas outlet, a dust discharge, and a means for gas inlet which will produce the gas rotation necessary to create the vortex. These three elements may be produced by tangential gas entrance or by axial gas entrance through a set of swirl vanes. Separated dust may be removed either axially or tangentially from the periphery. Dust may be removed from either the end opposite to the axial gas outlet or from the same end. There may be either one or a multiplicity of tangential inlets. The cyclone body may be completely cylindrical, completely conical, or made of both cylinders and cones. The gas outlet may be either cylindrical or conical. Cyclones in common use may be classified as follows:

1. Cyclones with tangential inlet and axial dust discharge.
    a. Large diameter ("conventional") cyclones.
    b. Small diameter ("high efficiency") cyclones.
2. Cyclones with tangential inlet and peripheral dust discharge.

3. Cyclones with axial inlet and axial dust discharge.
4. Cyclones with axial inlet and peripheral dust discharge.

This definition alone indicates the varieties of collectors that can be called cyclones. This section is therefore restricted to certain aspects of the simple cyclone. No attempt is made to define "the simple cyclone" (12:71).

There are several factors that influence a cyclone efficiency. They are, though not in the relative order of importance, as follows:

1. Cyclone diameter.
2. Gas outlet diameter.
3. Inlet width.
4. Cone length.
5. Particle size.
6. Pressure drop.

The first five factors shall be considered briefly in this chapter and their effects, if any, upon the pressure drop noted.

Cyclone diameter. Cyclones are generally divided into two classes, conventional and high efficiency. The high efficiency units simply have a smaller diameter than the conventional cyclones (8:100). If the diameter of a cyclone is changed from D_{c1} to D_{c2} and all other factors remain constant, it follows that the size particle collected should change also. The collected particle size changes from d_{p1} to d_{p2} as given by the following equation:

$$\frac{d_{p1}}{d_{p2}} = \sqrt{D_{c1}/D_{c2}} \qquad (2.02)$$

That is, the cyclone cut size changes as the square root of the cyclone diameter (14:44).

Effect of gas outlet diameter. Melvin First found that wide exit pipe diameters caused little effect on gas horizontal velocity. However, two downward flows resulted in the cyclone at the point where the inlet gas passed the restricted annular section. The downward flows were separated by an upward flow. With a narrow exit pipe the amount of gas that was allowed to flow out of the cyclone was reduced and again a recirculating downward stream was set up. These extra flows were associated, as might be expected, with increased pressure drop (14:92).

Effect of inlet width. The narrow width inlet cyclones give velocities four to five times as great in the cylindrical section of the cyclone and velocities as great or greater in the ascending spiral and gas outlet. The higher gas velocities will result in greater efficiency. First reached the conclusion that the higher velocities were the result of a higher degree of lapping of successive elements of gas in the cyclone. Increased internal shear as a result of lapping results in greater pressure drop (14:90).

Cone length. The definition of a cyclone makes no mention of a cone, because a cone is not a necessity for a cyclone to function properly. The cone's function is to deliver dust to a central point for ease of disposal and to reduce the length required for the main vortex to transform itself into the central core. The diameter at the apex of the cone should be greater than one-fourth the gas outlet diameter to prevent the vortex core from contacting the walls of the cone. When the core touches the wall collected material is forced into the exhaust gas stream. First found that if the cone is reduced in length too far a flow is created beneath the exit pipe that results in increased pressure drop (14:92).

Particle size. The centrifugal force on the particles in the gas stream forces them across the streamlines of gas flow toward the wall of the cyclone. The separating forces on the particle are given by the following equation:

$$F_s = \frac{M_p V_p^2}{gR} \qquad (2.03)$$

If we assume the gas velocity to be equal to the particle velocity and introduce the parameters for particle mass, the equation becomes

$$F_s = f\left[\frac{\rho_p \; d_p^{\;3} \; V_p \; R_p^{\;2N}}{gR^{(2N+1)}}\right] \; . \qquad (2.04)$$

The Stokes' Law equation for the force resisting the motion of a 3 to 100 micron particle through a gas is as follows:

$$F_R = f[K \; \mu D_p] \quad . \quad (16:217) \qquad (2.05)$$

These equations show that the separating forces increase with the cube of particle diameter while the resistance to particle flow toward the cyclone wall increases linearly with particle diameter. Since the particles entering are generally spread evenly over the cyclone inlet, the cyclone does not have a sharp size cut between the particles it passes and those it collects. A typical equation for determining a cyclone's cut size follows:

$$D_{theor} = \frac{C_o \; D_c^{\;1/2} \; Q_s^{\;1/4} \; \mu^{1/2}}{h^{1/4} \; \gamma_d^{\;1/2}} \quad . \quad (5:67) \qquad (2.06)$$

Design of the MHD Cyclone

The use of a cyclone collector is shown in the first quarterly report prepared for the Department of the Interior, Office of Coal Research. The logic behind use of a cyclone collector is that the low fabrication and operational costs for the collection efficiency makes it the most desirable unit. The first cyclone collector in the flow stream was tested 29 months later. The heat sink cyclone gave design information for fabrication of a water cooled model.

The first cyclone in the MHD circuit was the heat sink model. The unit was designed following standard design practices for high efficiency, medium cyclones (16:248). The design parameters used for the heat sink cyclone are shown in Figure 10. The only deviation from standard practice on this unit is the absence of the lower conical section. The unit was fabricated from an existing tank. The equipment flow train on the heat sink unit is shown in Figure 11. The design of the splitter plate and exit duct on the heat sink unit resulted in too high a mass flow rate through the cyclone. (Accurate velocity measurement was not possible due to the short duration of the runs.) The limiting exit velocity of 70 feet per second appeared, by consensus, to be exceeded. A subjective evaluation of the opacity of the exiting streams from the cyclone and the duct lead to the conclusion that two-thirds

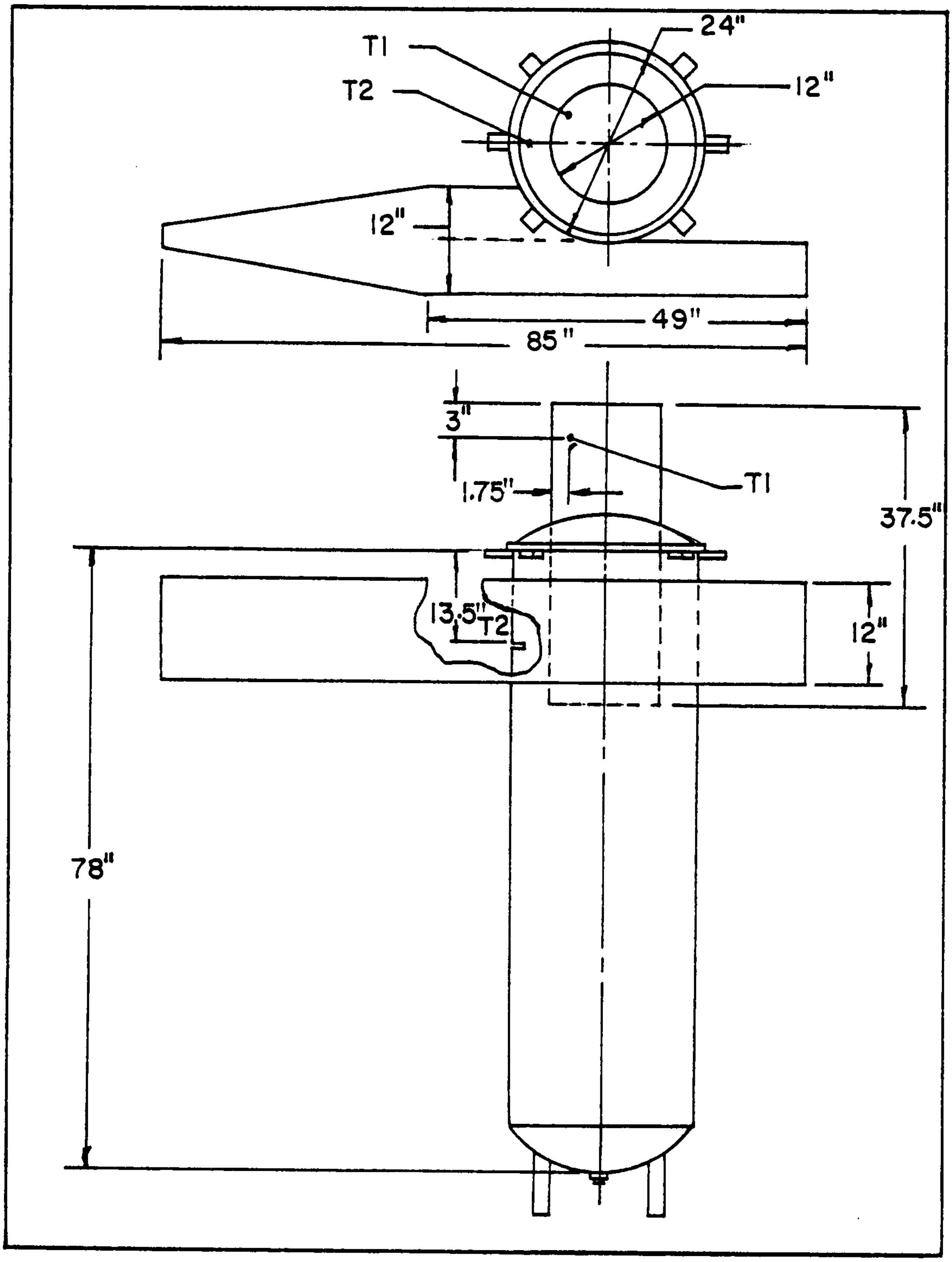

Figure 10. Heat Sink Cyclone Design.

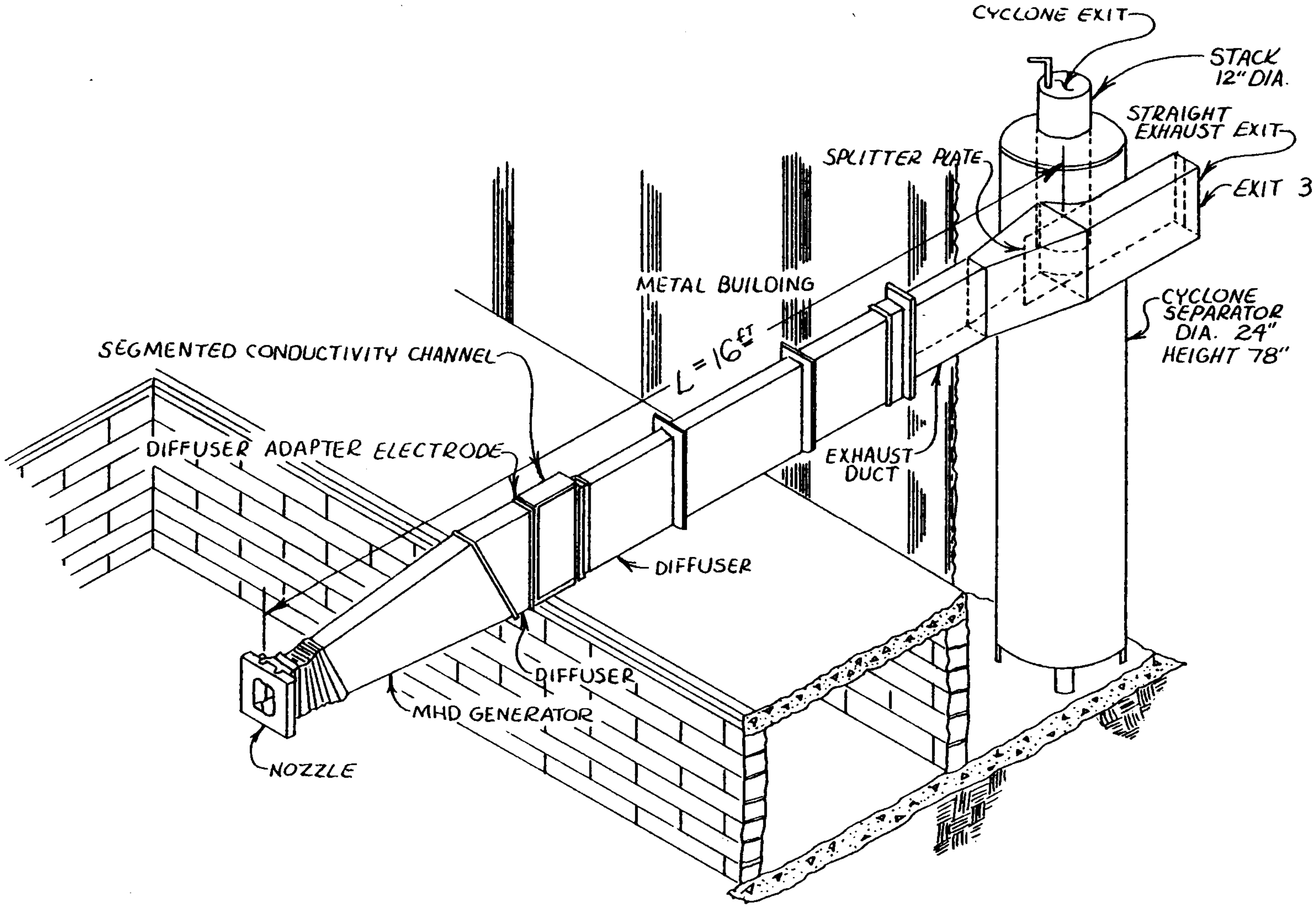

Figure 11. Heat Sink Cyclone Flow Train.

of the flow passed through the cyclone and one-third through the duct (17:5). The heat sink unit was designed to handle from 0.5 to 0.7 pounds per second (17:2).

The two water cooled cyclones were designed to handle the entire flow from the generator. They were designed following standard design procedures (18:13-44). The water cooled cyclones were designed as shown in Figure 12. The diameter of the water cooled units was 28 inches.

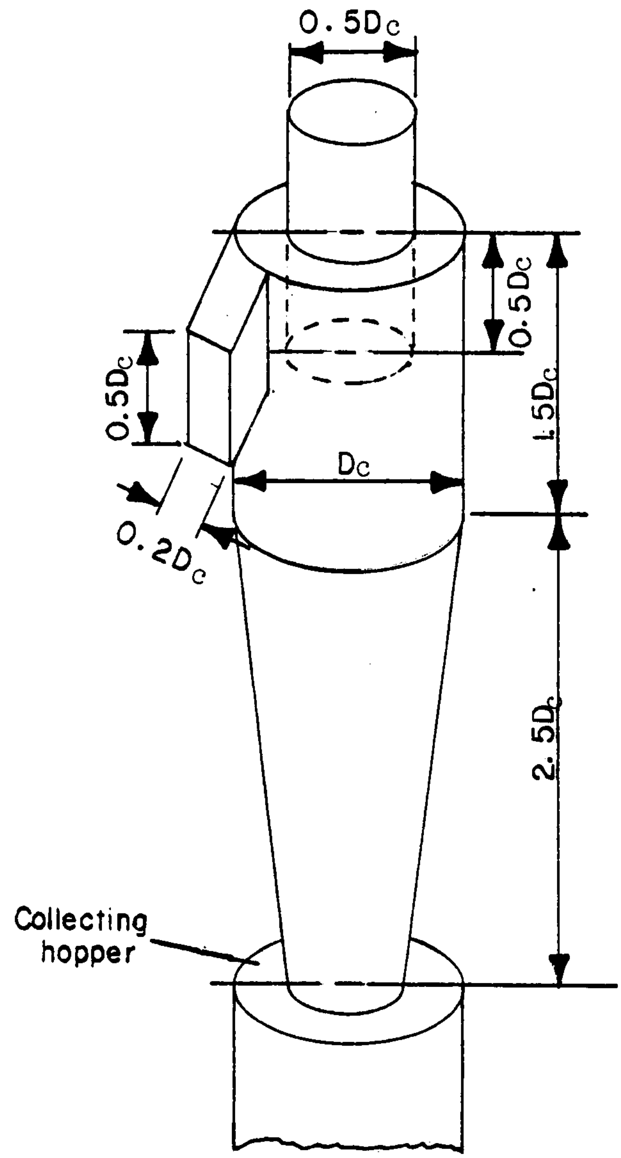

Figure 12. High Efficiency, Medium Throughout Cyclone Design.

Reference: Stairmand, C. J., and Kelsey, R. N., Cyclones and Industry, 1955, p. 1324.

CHAPTER III

UTSI MHD CYCLONE TEST DATA

Runs I-1424 through I-1449 on the UTSI MHD system gave information on slag-seed interaction, the water cooled cyclones' collection performance, coal feeding with potassium sulfate seed material, coal feeding with potassium carbonate seed material, and the operation of the radiant boiler test section. The tests on the radiant boiler are outside the scope of this thesis and shall not be mentioned further. The remainder of this thesis shall deal in a limited manner with the flow of seeded or unseeded coal to the combustion chamber and in detail, with the processing of the combustion products collected from the cyclones.

Information on runs I-1424 through I-1427 and 1428 through 1449 is given in Tables 3 and 4 respectively. The dates of the runs are given along with the duration of the test, the fuel used, and other information of importance.

Runs I-1424, I-1425, and I-1426 perplexed the test group until the source of the water that collected in the bottom of the cyclone was located. The water used to cool the unit was first suspected and a hole in the internal cyclone wall was sought. The collector was pressure tested with the generator down. The pressure testing showed no leaks and after run I-1425 it was determined that

TABLE 3

WATER COOLED CYCLONE TEST SERIES 1

Test No.*	Magnetic Field	Date	Fuel	Duration (Min)	Pertinent Info.
I-1424	Off	5/30/75	(Kerosene/O_2 Only)	1.33	Water in Cyclones
I-1425	Off	6/ 3/75	(Kerosene/O_2 Only)	14.63	Water in Cyclones
I-1426	Off	6/ 4/75	(Kerosene/O_2 Only)	6.17	Water in Cyclones
I-1427	Off	6/ 4/75	(Kerosene/Coal/O_2)	2.0/5.5	Tried Dump Valve

*Note: All runs after 1427 have one (1) minute preheat time on kerosene.

TABLE 4

WATER COOLED CYCLONE TEST SERIES 2

Test No.	Magnetic Field	Date	Time on Coal (Min)	Coal Lbs/Sec	Seed	Seed Lbs/Sec	Sample Wt. (Lbs) North Cyclone	Sample Wt. (Lbs) South Cyclone	Pertinent Info.
I-1428	Off	6/ 5/75	10.00	—	K_2SO_4		—		—
I-1429	Off	6/ 5/75	0.37	0.27	K_2SO_4	.027	—		Poor start—Gas leaks—Reworked boiler top
I-1430	Off	6/16/75	3.00	0.47	K_2SO_4	.047	—		—
I-1431	Off	6/16/75	6.00	0.447	K_2SO_4	.044	—		Hot spot on top boiler wall
I-1432	Off	6/18/75	8.93	0.410	K_2SO_4	.041	9.69		Hot spot South boiler wall—modified South boiler wall
I-1433	Off	6/26/75	17.60	0.390	K_2SO_4	.039	9.38		Lost water pressure
I-1434	Off	6/27/75	0.72	0.380	K_2SO_4		↓ -	↓	Hot spot North boiler wall—modified North wall
I-1435	Off	7/ 3/75	15.07	0.380	K_2SO_4	.038	9.56 -	8.94	Lost water pressure
I-1436	On	7/ 7/75	15.15	0.43	K_2SO_4	.043	23.94 -	25.56	Lost water pressure
I-1437	On	7/ 8/75	20.00	0.36	K_2SO_4	.036	13.44 -	17.13	—

TABLE 4 (Continued)

Test No.	Magnetic Field	Date	Time on Coal (Min)	Coal Lbs/Sec	Seed	Seed Lbs/Sec	Sample Wt. (Lbs) North Cyclone		Sample Wt. (Lbs) South Cyclone	Pertinent Info.
I-1438	On	7/11/75	0.42	—	K_2CO_3	—	↓	-	↓	Coal line plugged
I-1439	On	7/11/75	25.00	—	K_2CO_3	—	39.00	-	37.5	Load shorted
I-1440	On	7/15/75	6.17	0.34	K_2CO_3	.034	10.94	-	12.5	Coal line plugged
I-1441	On	7/15/75	2.67	0.33	K_2CO_3	.033	↓	-	↓	Coal line plugged
I-1442	On	7/16/75	1.25	0.33	K_2CO_3	.033	↓	-	↓	Coal line plugged
I-1443	On	7/16/75	3.33	0.49	K_2CO_3	.049	10.56	-	6.81	Hot spot South boiler wall, down-stream of modified tubes
I-1444	Off	7/21/75	1.25	0.49	None	—	↓	-	↓	Coal line plugged
I-1445	Off	7/22/75	5.30	0.49	None	—	↓	-	↓	Coal line plugged
I-1446	Off	7/22/75	0.83	0.49	None	—	13.89	-	11.88	Coal line plugged
I-1447	Off	7/25/75	12.17	0.49	None	—	26.19	-	20.31	Hot spot South boiler wall
I-1448	On	7/30/75	5.45	0.38	K_2CO_3 Seed—Not taken Injection					Coal flow stopped B-field short
I-1449	Off	7/31/75	16.38	—	Did not operate—Not taken					Objective to burn up unseeded coal

↓ — Flyash not removed from cyclone after this test.

the water was a by-product of near perfect combustion of kerosene.

The seed material used in the majority of the test runs was potassium sulfate. The potassium sulfate was mixed in powdered form with the pulverized coal. The ratio of seed material to coal may be seen in Table 4 as 10 percent. The collection efficiency of the cyclones is given in Table 5. The mass efficiency of seeded runs is lower due to the lower grade efficiency of the seed material. Potassium sulfate seed was used in the majority of runs because this compound showed less affinity for moisture than other potassium compounds. The tendency of potassium carbonate to agglomerate, causing plugged generator feed lines, is shown in Table 4 runs I-1438, I-1440, I-1441, I-1442, and I-1448.

The combustion products were collected by emptying the cyclone's hopper after each successful run, and by isokinetic sampling of the cyclone exhaust. The sample collected from the cyclone hopper was weighed, separated by coarse screening, and washed using the following procedure:

1. Place filters in two filter cups and weigh.
2. Weigh 4-200ml beakers.
3. Place half of total unwashed chunks into one of the four beakers and reweigh.
4. Place approximately 6 teaspoons of fine dust into another beaker, using a clean spoon. Reweigh the beaker.

TABLE 5

CYCLONE COLLECTION EFFICIENCY

Test No.	Magnetic Field	Seed	Cyclone Input, Lbs	Sample Collected, Lbs	ε,%
I-1434 - I-1435	Off	K_2SO_4	88.92	18.5	21
I-1436	On	K_2SO_4	98.1	49.5	50
I-1437	On	K_2SO_4	106.7	30.6	29
I-1440	On	K_2CO_3	31.1	23.4	75
I-1441 - I-1443	On	K_2CO_3	43.4	17.3	40
I-1444 - I-1446	Off	None	31.9	25.8	81
I-1447	Off	None	52.6	46.50	88

5. Place 75cc of water into chunk beaker and heat for approximately 5.5 minutes on a hotplate. Stir the mixture constantly. Do not allow the water to boil; keep water between 90°-95°C. Leave the mixture on the hotplate after the 5.5 minute period with the hotplate unplugged.
6. Place filter cup #1 atop large vacuum beaker. Wet filter to keep it in place. Pour washed chunk into vacuum beaker through filter. Note: A rubber disk is used to seal the filter cup to the beaker.
7. Repeat (#5) and (#6), using the same chunks and beakers.
8. Add a bit more water to the chunk beaker and scrape it clean with a rubber-tipped glass stirrer. Pour liquid into vacuum beaker.
9. Repeat (#8).
10. Repeat (#8).
11. Pour material from vacuum beaker into one of the remaining beakers from (#2).
12. Rinse vacuum beaker with approximately 55cc of water and pour liquid into beaker from step (#11).
13. Repeat steps (#5) through (#12) with fine material placing filter #2 into fines beaker and the liquid from the vacuum bottle into last empty beaker.

14. Place beakers from step (#11) and step (#13) in a 75°C oven and allow to dry.
15. Place dried sample in desiccant jar for 24 hours before weighing.
16. Weigh dried samples in beakers to obtain sample weight.
17. Place samples in containers and prepare to send to a commercial laboratory for chemical analysis (19).

The exhaust material was collected following E.P.A. guidelines for determination of particulate emissions from stationary sources. The sample setup consisted of a 3/8-inch sampling probe, a thimble holder, a fiberglass thimble, and vacuum hoses connecting 4 impingers in series with the thimble holder and vacuum pump. The first three impingers were filled with distilled water and the fourth impinger was dry. The four impingers were kept in an ice pack and were followed by a dry gas meter and a vacuum pump. A schematic of the sample train is shown in Figure 13. The particulate collected in the fiberglass thimble was on occasion washed following the aforementioned procedures. The solution remaining in the impingers after the end of a run was poured into a sample jar.

The results of washing the material collected in the cyclone hopper follow. The beakers and filters used for weighing samples in Table 6 were numbered for ease of

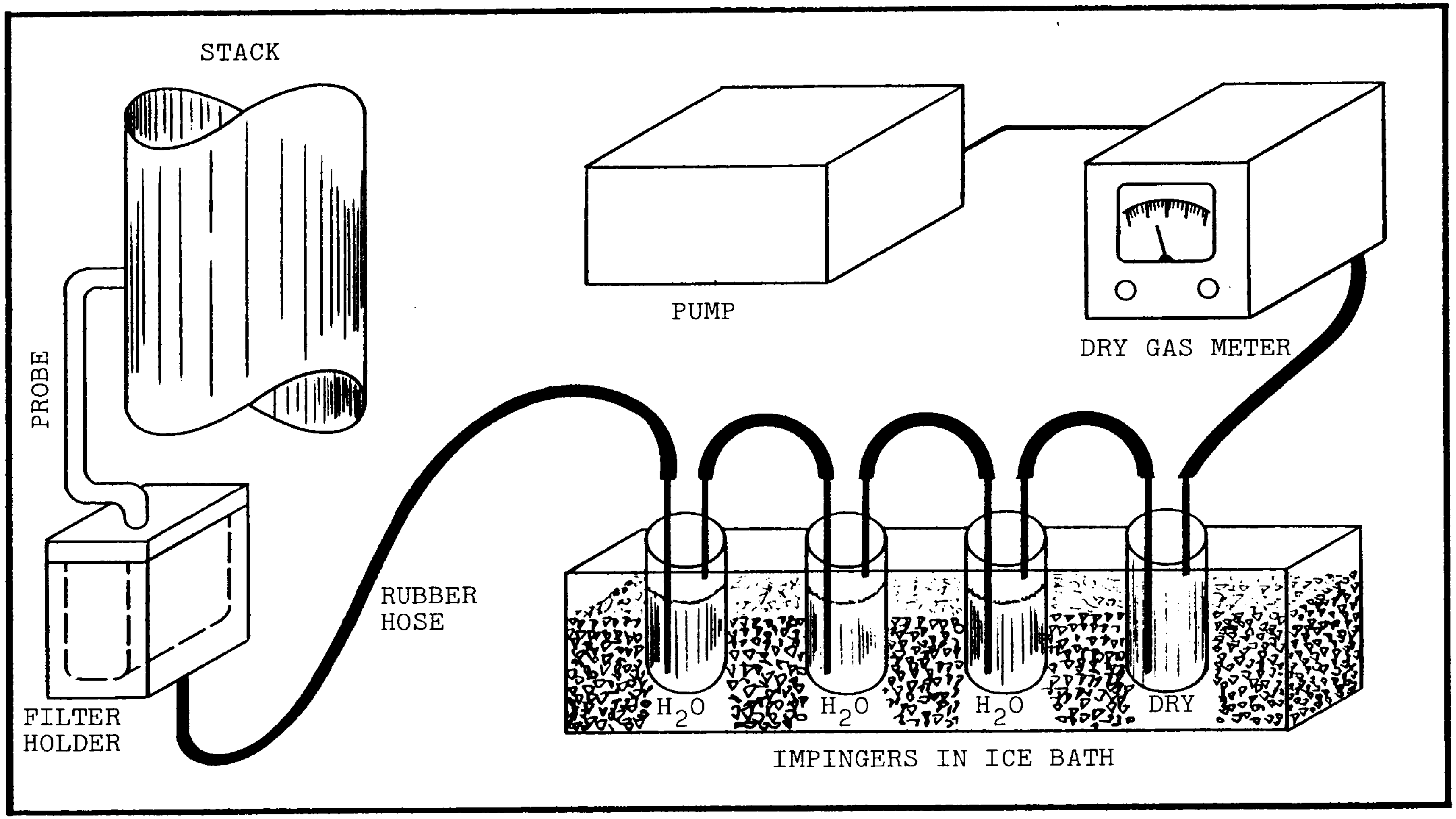

Figure 13. Schematic of MHD Cyclone Sampling Train.

TABLE 6

SAMPLE WASH DATA

DATA	RUN NUMBER 1431	1432	1433	1436	1437	1437[2]	1440	1440[2]	1440[2,3]	1440	1447
Date of Wash	6/17/75	7/2/75	7/7/75	7/9/75	7/9/75	9/5/75	7/5/75	8/21/75	9/5/75	9/5/75	7/25/75
Wt. of Unwashed Fines	15.0700 gr.	14.8750 gr.	43.8321 gr.	27.9307 gr.	26.7807 gr.	--	15.0208 gr.	--	--	--	15.7870 gr.
Wt. of Washed Fines	10.3694 gr.	9.5415 gr.	28.9261 gr.	18.0346 gr.	17.1841 gr.	--	9.1912 gr.	--	--	--	12.5936 gr.
Wt. of Soluble Fines	4.7354 gr.	5.4335 gr.	14.3968 gr.	4.7459 gr.	9.5407 gr.	--	5.5023 gr.	--	--	--	3.2424 gr.
Percentage of Material in a Soluble Fines Sample	31.4%	36.5%	32.9%	17%	35.6%	--	36.6%	--	--	--	20.5%
Wt. of Unwashed Chunks	10.9290 gr.	15.2694 gr.	35.0660 gr.	35.4882 gr.	48.6582 gr.	41.7069 gr.	35.3419 gr.	39.9335 gr.	41.6644 gr.	44.6152 gr.	35.9201 gr.
Wt. of Washed Chunks	10.4577 gr.	14.3337 gr.	34.4017 gr.	35.1838 gr.	47.3530 gr.	40.9782 gr.	33.0603 gr.	36.3529 gr.	39.7517 gr.	42.1874 gr.	35.8464 gr.
Wt. of Soluble Chunks	0.4685 gr.	0.9877 gr.	0.7043 gr.	0.3040[1] gr.	1.1994 gr.	0.8181 gr.	2.2523 gr.	3.5016 gr.	2.0170 gr.	2.502 gr.	0.0916 gr.

TABLE 6 (continued)

DATA	RUN NUMBER										
	1431	1432	1433	1436	1437	1437[2]	1440	1440[2]	1440[2,3]	1440	1447
Percentage of Soluble Material in Chunk Sample	4.3%	6.5%	2.0%	0.9%	2.5%	2.0%	6.4%	8.8%	4.8%	5.6%	0.2%
Seed Material	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2CO_3	K_2CO_3	K_2CO_3	K_2CO_3	None
Cyclone Sampled	North	North	North	South	South	South	South	South	South	South	North

[1] Scale out of order, arrived at by subtraction

[2] Sample ground, then washed

[3] Sample blown off with air hose before processing

handling. The exhaust sampling equipment was also monitored and the collected particulate retained for analysis. Table 7 shows information obtained from the source sampling equipment.

The collected samples were mailed to Barrow-Agee Laboratory for chemical analysis and to a Scanning Electron Microscope Lab for sample photographing. The Barrow-Agee sample analysis methods follow:

1. Moisture via gravimetric oven drying at 105°C.
2. "K" via atomic absorption using nitric and hydrochloric acids.
3. $Si\ O_2$.
   (a) Dehydrate and dissolve HCl/Nitric acid.
   (b) Evaporate to dryness.
   (c) Redissolve in HCl.
   (d) Filter and wash.
   (e) Ash in crucible at 1000°C and weigh.
   (f) Add dry H_2SO_4 and HCl and evaporate.
   (g) Reheat and determine weight loss.
4. SO_4 precipitates via treatment with $BaSO_4$.
   (a) Filter on Whatman 40.
   (b) Wash.
   (c) Ash.
   (d) Weigh.

TABLE 7

THIMBLE SAMPLING DATA

DATA	RUN NUMBER 1431	1432	1433	1434	1435	1436	1437	1438/ 1439	1440	1443	1445[1]	1447
Thimble Collection												
Date of Run	6/16/75	6/18/75	6/26/75	6/27/75	7/3/75	7/7/75	7/8/75	7/11/75	7/15/75	7/16/76	7/22/75	7/25/75
Collected Mass, gr.	1.9183	1.8718	2.1194	0.0619	3.0048	0.7240	1.4043	3.7698	3.133	2.4307	0.9060	1.2397
Flow Meter Reading, ft^3	7.291	8.402	17.960	0.376	21.062	8.935	6.187	5.916	4.266	3.521	4.661	9.657
Sampling Time, min.	5.00	8.53	18.15	0.22	15.00	5.00	4.00	--	3.00	2.50	3.00	6.00
Collection Rate												
1) gr/ft^3	0.26	0.22	0.12	0.16	0.14	0.08	0.23	0.64	0.73	0.69	0.19	0.13
2) gr/min	0.38	0.22	0.12	0.28	0.20	0.14	0.35	--	1.04	0.97	0.30	0.21
Seed Material	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2SO_4	K_2CO_3	K_2CO_3	K_2CO_3	None	None
Thimble Wash												
Date of Wash			8/8/75									

TABLE 7 (continued)

DATA	RUN NUMBER 1431	1432	1433	1434	1435	1436	1437	1438/1439	1440	1443	1445[1]	1447
Thimble Wash (continued)												
Pre-Wash Solids Wt., gr.			1.7325									
Post-Wash Solids Wt., gr.			0.7931									
Wt. of Dried Water Soluble Material, gr.			0.9457									
Percentage of Soluble Material in Sample			54.6%									

[1]Sample probe does not remain on cyclone wall; for this sample it is traversed across the cyclone diameter.

5. Al and Fe .

   (a) Precipitate with NH_4OH , get Al and Fe as NH_3OH group.

   (b) Ash at 1000°C.

   (c) Weight ⟶ $Al_2O_3 + Fe_2O_3$.

   (d) Dichloremate method (Titrate for Fe_2O_3) (Calc. to Fe) .

   (e) Use value of Fe_2O_3 to get Al_2O_3 from total, calculate Al .

6. Cu , Ca , and Na , via atomic absorption using same nitric and HCl acid solutions as for K .

7. Total sulfur with Leakco furnace, titrator where $S_{free} = S_{Tot} - S_{SO_2}$.

8. Carbon to ash and measure weight change.

The Barrow-Agee sample codes and the Scanning Electron Microscope sample codes follow in order of sample numbers:

1. Cyclone flyash, fine unwashed dust.
2. Cyclone chunks, unwashed.
3. Furnace cement powder.
4. Fiberglass thimble, unwashed.
5. First impinger, liquid.
6. Second impinger, liquid.
7. Third impinger, liquid.
8. Cyclone flyash, fine washed dust.
9. Cyclone chunks, washed.

10. Cyclone flyash, long "nail-like" pieces.
11. Radiant boiler exit, wall coating.
12. Radiant boiler entrance, rear of step.
13. Evaporated washings from dust.
14. Evaporated washings from chunks.
15. Fiberglass thimble, washed.
16. Evaporated washings from thimble.
17. Coal.
18. No sample.
19. No sample.
20. Powder from thimble.
21. Powder from probe and probe body.
22. Cyclone flyash, fine unwashed dust.
23. Cyclone flyash, fine washed dust.
24. Radiant boiler entrance, rear of step.
25. Radiant boiler exit, wall covering.
26. Cyclone chunks, washed.
27. Evaporated washings from dust.

The findings of Barrow-Agee represent the heart of this thesis. They are given in Table 8 through Table 23.

The tables show that 50 percent to 70 percent of the potassium in the fine flyash samples was removed by washing, 50 percent to 80 percent was removed by washing the chunk samples, and 93.9 percent was removed by washing the single washed filter sample. These efficiencies are not as high as desired, but better results will certainly be obtained

TABLE 8

SAMPLE 1--CYCLONE FLYASH, FINE UNWASHED DUST

PERCENT	RUN NUMBER 1431	1437	1440	1447
Moisture	0.14	--	--	--
Potassium as K	12.65	17.20	13.20	7.90
Silica	24.70	23.56	30.86	27.46
Sulfates, as SO_4	19.14	21.09	20.15	10.56
Aluminum*	28.19	7.41	4.68	4.39
Iron*	8.78	6.86	8.40	7.28
Copper*	9.24	0.18	0.18	0.23
Calcium*	0.13	1.07	1.86	1.90
Sodium*	1.75	0.58	0.46	0.72
Free Sulfur	0.7	0.2	0.2	0.2
Free Carbon	4.6	5.91	8.2	10.0
Potassium Sulfate	--	38.26	29.42	17.61

*Given as Aℓ, Fe, Cu, Ca, and Na, respectively, for Runs 1437, 1440, and 1447.

TABLE 9

SAMPLE 2--CYCLONE CHUNKS, UNWASHED

PERCENT	RUN NUMBER				
	1437	1437	1440	1440	1447
Moisture	--	0.02	--	0.12	--
Potassium, as K	1.42	0.52	1.20	1.22	0.70
Silica, as SiO_2	40.42	--	42.48	--	13.39
Sulfates, as SO_4	1.68	--	2.74	--	1.96
Potassium Sulfate	3.05	0.63	2.67	2.72	1.56
Aluminum, As Al	14.29	16.58	13.89	13.56	15.32
Iron, as Fe	7.28	--	9.10	--	11.20
Copper, as Cu	0.05	0.002	0.085	0.012	0.10
Calcium, as Ca	1.86	2.18	2.50	1.17	0.86
Sodium, as Na	0.52	0.40	0.42	0.40	0.47
Free Sulfur	0.0	--	0.0	--	0.0
Free Carbon	0.0	--	0.1	--	0.2
Total Iron	--	9.24	--	11.06	
Fixed Carbon	--	0.1	--	0.3	
Sulfur, as S	--	0.12	--	1.25	
Silicon, as Si	--	16.34	--	14.48	

TABLE 10

SAMPLE 3--FURNACE CEMENT POWDER

PERCENT	RUN NUMBER 1431
Aluminum Oxide	25.10
Magnesium Oxide	0.01
Zirconium Oxide	69.38
Potassium	0.03
Sulfates, as SO_4	0.012
Calcium Oxide	7.05

TABLE 11

SAMPLE 4--FIBERGLASS THIMBLE, UNWASHED

PERCENT	RUN NUMBER 1433	1437	1440	1447
Potassium, as K	14.53	14.18	12.88	19.80
Potassium Sulfate	32.45	31.67	26.70	44.13
Silica, SiO_2	18.87	19.43	22.22	23.00
Sulfates, as SO_4	33.80	40.61	33.80	26.65
Aluminum, as Al	4.20	2.58	3.30	1.75
Iron, as Fe	6.69	6.43	6.50	4.90
Copper, as Cu	0.14	0.14	0.14	0.075
Calcium, as Ca	0.92	2.12	1.19	1.70
Sodium, as Na	0.30	0.29	0.30	0.82
Free Sulfur	0.2	0.3	0.0	0.6
Free Carbon	1.2	3.11	0.0	0.4

TABLE 12

SAMPLE 5--FIRST IMPINGER, LIQUID

	RUN NUMBER				
	1431	1436*	1437	1440	1447
Parts per Million					
Potassium, as K	145		690	52	88
Silica, as SiO_2	--		--	12	23
Sulfates, as SO_4	2,800		2,581	109	729
Potassium Sulfate	--		--	109	184
Aluminum, as Al	--		--	0.22	1.22
Iron, as Fe	--		--	0.40	0.48
Copper, as Cu	--		--	0.12	5.1
Calcium, as Ca	--		--	5	2
Sodium, as Na	--		--	22	8
Free Sulfur	--		--	0.0	0.0
Free Carbon	--		--	0.0	0.0
Percent					
Moisture		20.12			
Potassium, as K		5.12			
Potassium Sulfate		11.12			
Total Iron		1.96			
Fixed Carbon		0.2			
Sulfur, as S		2.05			
Sodium, as Na		0.52			
Aluminum, as Al		3.83			
Calcium, as Ca		1.93			
Silicon, as Si		6.81			
Copper, as Cu		0.04			

*This sample was dried and then analyzed.

TABLE 13

SAMPLE 6--SECOND IMPINGER, LIQUID

PARTS PER MILLION	RUN NUMBER 1431	1437	1440	1447
Potassium, as K	42	108	46	40
Silica, as SiO_2	--	--	62	10
Sulfates, as SO_4	775	1,494	809	211
Potassium Sulfate	--	--	96	84
Aluminum, as Al	--	--	1.12	0.30
Iron, as Fe	--	--	0.88	0.28
Copper, as Cu	--	--	0.1	0.9
Calcium, as Ca	--	--	2	2
Sodium, as Na	--	--	8	6
Free Sulfur	--	--	0.0	0.0
Free Carbon	--	--	0.0	0.0

TABLE 14

SAMPLE 7--THIRD IMPINGER, LIQUID

PARTS PER MILLION	RUN NUMBER 1431	1437	1440	1447
Potassium, as K	25	54	52	82
Silica, as SiO_2	--	--	45	22
Sulfates, as SO_4	539	950	21	1,473
Potassium Sulfate	--	--	109	172
Aluminum, as Al	--	--	1.22	1.18
Iron, as Fe	--	--	0.68	0.48
Copper, as Cu	--	--	0.11	0.5
Calcium, as Ca	--	--	2	2
Sodium, as Na	--	--	5	6
Free Sulfur	--	--	0.0	0.0
Free Carbon	--	--	0.0	0.0

TABLE 15

SAMPLE 8--CYCLONE FLYASH, FINE WASHED DUST

PERCENT	RUN NUMBER			
	1431	1437	1440	1447
Moisture	0.46	--	--	--
Potassium*	6.05	3.80	5.80	0.90
Silica*	33.77	44.21	32.65	33.46
Sulfates, as SO_4	1.88	5.12	0.46	2.26
Potassium Sulfate	3.41	8.47	0.83	2.01
Aluminum*	14.18	9.89	8.71	5.40
Iron*	11.48	8.26	14.84	21.28
Copper*	0.18	0.25	0.29	0.29
Calcium*	1.75	0.36	1.32	4.20
Sodium*	0.38	0.52	0.60	0.40
Free Sulfur	0.1	0.0	0.1	0.1
Free Carbon	9.4	9.51	10.2	11.1

*Taken as K, SiO_2, Al, Fe, Cu, Ca, and Na for runs other than 1431.

TABLE 16

SAMPLE 9--CYCLONE CHUNKS, WASHED

	RUN NUMBER							
PERCENT	1431	1437	1437	1437[1]	1440	1440[1]	1440[2]	1447
Moisture	0.13	--	--	0.02	--	0.02	0.10	--
Potassium*	6.50	1.23	0.52	0.40	5.92	0.41	0.80	0.46
Silica*	34.93	36.49	35.90	--	34.47	--	--	34.57
Sulfates, as SO_4	0.15	0.56	0.43	--	1.19	--	--	0.19
Aluminum*	15.13	16.69	16.82	16.36	9.52	17.17	14.96	18.37
Iron*	11.62	9.52	7.84	--	15.40	--	--	10.22
Copper*	0.06	0.05	0.003	0.003	0.34	0.006	0.004	0.05
Calcium*	3.75	2.00	2.11	2.46	2.11	2.11	2.36	1.20
Sodium*	0.32	0.51	0.40	0.38	0.50	0.41	0.40	0.52
Potassium Sulfate	0.27	1.02	0.94	0.89	2.16	0.69	1.78	0.34
Free Sulfur	0.0	0.0	0.07	--	0.0	--	--	0.0
Free Carbon	0.1	0.2	0.0	--	0.1	--	--	0.1
Total Iron	--	--	--	9.66	--	7.77	9.87	--
Fixed Carbon	--	--	--	0.0	--	0.0	0.2	--
Sulfur, as S	--	--	--	0.24	--	0.23	0.38	--
Silicon, as Si	--	--	--	16.44	--	15.84	15.12	--

*Taken as K, SiO_2, Al, Fe, Cu, Ca, and Na for runs other than 1431.

[1]These samples were ground, then washed.

[2]This sample was washed, ground, then rewashed.

TABLE 17

SAMPLE 10--CYCLONE FLYASH, LONG "NAIL-LIKE" PIECES

PERCENT	RUN NUMBER 1431	1447
Moisture	0.12	--
Potassium	6.35	0.50*
Silica, as SiO_2	38.60	34.88
Sulfates, as SO_4	0.20	0.45
Aluminum	14.50	16.77*
Iron	11.27	9.24*
Copper	0.05	0.075*
Calcium	2.96	1.10*
Sodium	0.50	0.53*
Potassium Sulfate	0.36	0.82
Free Sulfur	0.0	0.1
Free Carbon	0.0	0.1

*Potassium as K, Aluminum as Al, Iron as Fe, Copper as Cu, Calcium as Ca, and Sodium as Na.

TABLE 18

SAMPLE 11--RADIANT BOILER EXIT, WALL COATING

PERCENT	RUN NUMBER 1431
Moisture	0.05
Potassium	7.65
Silica	34.29
Sulfates	0.31
Aluminum	16.67
Iron	11.20
Copper	0.07
Calcium	3.18
Sodium	0.52
Potassium Sulfate	0.56
Free Sulfur	0.0
Free Carbon	0.3

TABLE 19

SAMPLE 13--EVAPORATED WASHINGS FROM DUST

PERCENT	RUN NUMBER 1431	1437	1440	1447
Potassium	41.25	42.70	42.70*	43.20*
Silica	0.12	0.01*	0.11	0.13*
Sulfates	53.75	53.75*	53.96*	53.96*
Potassium Sulfate	91.93	95.16	95.16	96.28
Aluminum	0.05	0.81*	1.31*	0.42*
Iron	1.12	0.32*	0.24*	0.14*
Copper	0.01	0.002*	0.015*	0.025*
Calcium	1.86	1.50*	1.18*	0.70*
Sodium	0.50	0.50*	0.52*	0.63*
Free Sulfur	0.05	0.0	0.0	0.0
Free Carbon	0.1	0.2	0.1	0.0

*Potassium as K, Silica as SiO_2, Sulfates as SO_4, Aluminum as Al, Iron as Fe, Copper as Cu, Calcium as Ca, and Sodium as Na for runs other than 1431.

TABLE 20

SAMPLE 14--EVAPORATED WASHINGS FROM CHUNKS

PERCENT	RUN NUMBER			
	1431	1437[1]	1440	1440[1]
Potassium	43.80	0.92*	42.90*	2.36*
Silica	0.03	--	0.08	--
Sulfates	55.16	--	53.20*	--
Potassium Sulfate	97.62	2.05	96.50	2.01
Aluminum	0.03	1.28*	0.80*	5.47*
Iron	0.28	--	0.20*	--
Copper	0.01	0.001*	0.010*	0.003*
Calcium	0.57	2.50*	1.02*	1.20*
Sodium	0.48	0.38*	0.60*	0.40*
Free Sulfur	0.0	--	0.0	--
Free Carbon	0.0	--	0.0	--
Moisture	--	0.57	--	28.30
Total Iron	--	8.40	--	3.71
Fixed Carbon	--	0.5	--	6.12
Sulfur, as S	--	0.92	--	1.11
Silicon, as Si	--	13.85	--	7.84

*In these samples Potassium as K, Sulfates as SO_4, Aluminum as Al, Iron as Fe, Copper as Cu, Calcium as Ca, and Sodium as Na are taken.

[1]These samples represent the soluble portions of Sample 9, 1437[1] and Sample 9, 1440[1].

TABLE 21

SAMPLE 15--FIBERGLASS THIMBLE, WASHED

PERCENT	RUN NUMBER 1433
Potassium, as K	1.22
Silica, as SiO_2	22.22
Sulfates, as SO_4	2.22
Potassium Sulfate	2.54
Aluminum	6.72
Iron, as Fe	8.92
Copper, as Cu	0.08
Sodium, as Na	0.42
Free Sulfur	0.2
Free Carbon	0.2
Calcium, as Ca	2.22

TABLE 22

SAMPLE 16--EVAPORATED WASHINGS FROM THIMBLE

PERCENT	RUN NUMBER 1433
Potassium, as K	40.1
Silica, as SiO_2	0.20
Sulfates, as SO_4	48.77
Potassium Sulfate	88.46
Aluminum, as Al	0.22
Iron, as Fe	1.12
Copper, as Cu	0.05
Calcium, as Ca	2.20
Sodium, as Na	0.60
Free Sulfur	0.1
Free Carbon	0.1

TABLE 23

SAMPLE 17--COAL

PERCENT	RUN NUMBER 1437	1447
Moisture	0.23	0.09
Ash	14.69	17.58
Volatile Matter	47.10	46.30
Fixed Carbon	37.98	36.03
Thermal Value	9,200 BTU/lb.	9,500 BTU/lb.
Sulfur	3.23	2.99
Chlorine	0.03	0.06
Silicon	22.22	17.41
Aluminum	2.88	2.96
Iron	11.42	13.53
Titanium	0.49	0.50
Calcium	1.72	1.92
Magnesium	0.52	0.51
Sodium	0.58	0.52
Potassium	1.82	1.92
Copper	0.34	0.24

with less crude methods. The use of automatic equipment capable of washing the samples at elevated temperatures might also be added to the system.

It is interesting to note from Table 8 and Table 9 that the majority of the seed material is present in the fine dust rather than in the chunks. It is also interesting to note that from the scanning electron microscope analysis and from the X-ray analysis that the seed is present as a covering over the slag (20:3-5). This finding is verified by Table 15 and Table 16, which show the amount of seed remaining after sample water washing. The accumulation of K_2SO_4 and K_2CO_3 as a covering is due to the slag forming at what are vapor phase temperatures for the seed. Therefore, the higher percentages of seed material on the smaller slag particles can be attributed to their greater surface area per unit volume (21).

CHAPTER IV

EVALUATION OF SEED RECOVERY METHODS

This section of the study is devoted to an analysis of the effectiveness of the cyclonic seed recovery process. The results given are for the washed and unwashed flyash as noted. Run 1437 was chosen as the run to be presented due to its 20-minute length, the magnetic field being on, and the K_2SO_4 seed used. Since repeatability was difficult in the early stages of generator testing, analyzing one run appeared the only logical method of insuring unbiased results.

Proper evaluation of the seed recovery efficiency of the cyclone collecting system requires a mass balance between seed input and collected seed. An analysis of the K_2SO_4 balance follows for run I-1437:

The seed input is given from Table 4 as:

$$S_I = \frac{.036 \text{ lb seed}}{\text{sec}} * \frac{60 \text{ sec}}{\text{min}} * 20 \text{ min}$$

$$S_I = 43.20 \text{ lbs} .$$

The breakdown by weight of chunks and dust in the sample collected was approximately 57 percent chunks and 43 percent dust (22). Therefore the weight of chunks and dust collected is

$$W_C = W_T * 0.57$$

$$= 60.57 \text{ lbs} * 0.57$$

$$W_C = 34.49 \text{ lbs}$$

and

$$W_D = W_T * 0.43$$

$$= 60.57 \text{ lbs} * 0.43$$

$$W_D = 26.05 \text{ lbs} .$$

The K_2SO_4 recovered from washing the dust is

$$S_D = W_D * 0.356 \frac{\text{lb } K_2SO_4}{\text{lb dust}}$$

$$= 26.05 \text{ lbs} * 0.356 \frac{\text{lb } K_2SO_4}{\text{lb dust}}$$

$$S_D = 9.27 \text{ lbs} \text{ , assuming soluble component is } K_2SO_4 .$$

The K_2SO_4 recovered from washing the chunks is

$$S_{c1} = W_c * 0.0249 \frac{\text{lb } K_2SO_4}{\text{lb chunk}}$$

$$S_{c1} = 34.49 \text{ lbs} * 0.0249 \frac{\text{lb } K_2SO_4}{\text{lb chunk}}$$

$$S_{c1} = 0.86 \text{ lb} .$$

The K_2SO_4 recovered from rewashing the chunks after crushing is

$$S_{c2} = (W_c - S_{c1}) * 0.0197 \frac{\text{lb } K_2SO_4}{\text{lb crushed chunk}}$$

$$S_{c2} = 0.66 \text{ lb} .$$

The material collected in the sample probe filter during the four minute sample time is derived from Table 21.

When the 3/8-inch sample probe conditions are taken over the entire outlet, the total exhaust is given as

$$G_L = 13.48 \text{ gr/SCF} \quad ;$$

therefore,

$$W_E = 13.8 \text{ lbs} \quad .$$

The K_2SO_4 in the exhaust is derived using Table 15 and Table 16 as

$$S_E = W_E * 0.546 \frac{\text{lbs } K_2SO_4}{\text{lb tot.}}$$

$$= 7.53 \text{ lbs} \quad .$$

A similar derivation on Table 12, Table 13, and Table 14 lead to a calculation of

$$S_{IM} = 18.41 \text{ lbs} \quad .$$

The summation of collected K_2SO_4 is

$$S_o = S_o + S_{c1} + S_{c2} + S_E + S_{IM}$$

$$= 36.74 \text{ lbs} \quad .$$

This gives us a recovery rate of

$$R_R = \frac{S_o}{S_I} * 100$$

$$R_R = 85 \text{ percent} \quad .$$

The insoluble portion of K_2 in the slag chunks is given by

$$I_C = W_C * .038 \frac{\text{lb } K_2}{\text{lb chunk}}$$

$$I_C = 1.31 \text{ lb K} \quad .$$

The insoluble portion of K_2 in the hopper dust is given by

$$I_D = W_D * .0123 \frac{\text{lb } K_2}{\text{lb chunk}}$$

$$I_D = 0.32 \text{ lb K} \quad .$$

The insoluble portion of K_2 in the cyclone exhaust is given by

$$I_E = W_E * 0.007 \frac{\text{lb } K_2}{\text{lb dust}}$$

$$I_E = 0.09 \text{ lb} \quad .$$

The summation of insoluble material is given by

$$I_T = I_C + I_D + I_E$$

$$I_T = 1.72 \text{ lb } K_2 \quad .$$

This is equivalent to 3.84 lbs of K_2SO_4 . Therefore, the percentage of seed material lost to the slag is

$$R_L = \frac{3.84 \text{ lbs } K_2SO_4}{S_I} * 100$$

$$R_L = 8.9 \text{ percent} \quad .$$

The percentage of unaccounted-for seed material is:

$$R_u = 100 - R_L - R_R$$

$$R_u = 6.1 \text{ percent} \quad . \quad (22)$$

Recent experimental analysis with seed recovery rates has demonstrated a 95 percent seed recovery rate (23). Accordingly, it is expected that a 96 percent seed recovery rate will be a reasonably attainable goal for commercial plants. It is worthwhile to reiterate the fact that capital and fuel costs, particularly capital costs, dwarf the cost of seed material (3:73), for 96 percent recovery.

Conclusions

The mass efficiency of the cyclone collectors, as given in Table 5, varied from an average of 43 percent for seeded runs to an average of 84.5 percent for unseeded runs. This variation in mass efficiency is speculated to result from the lower grade efficiency, due to particle size, of the cyclone flyash collectors as seed collectors. The average seeded run has a cyclone seed feed percentage of 40 percent. This percentage increases as the ash content of the coal used decreases.

The results of the seed recovery tests were quite promising. The 85 percent seed recovery rate obtained from simple water washing of cyclone samples coupled with the 6.1 percent unaccounted-for seed gives 91.1 percent seed that could be recovered. This figure is well into the neighborhood of the 96 percent rate mentioned earlier in this chapter for commercial plants. There is hope that the 8.9 percent seed lost to slag could also be recovered by washing with a chemical other than water.

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